

Quantum Counterfactuals and Locality

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Abstract

Stapp's counterfactual argument for quantum nonlocality based upon a Hardy entangled state is shown to be flawed. While he has correctly analyzed a particular framework using the method of consistent histories, there are alternative frameworks which do not support his argument. The framework dependence of quantum counterfactual arguments, with analogs in classical counterfactuals, vitiates the claim that nonlocal (superluminal) influences exist in the quantum world. Instead it shows that counterfactual arguments are of limited use for analyzing these questions.

1 Introduction

Henry Stapp [1] has challenged an argument by the author [2, 3] which claims to demonstrate that quantum mechanics is a local theory, in the sense that it contains no long-range dynamical influences. Stapp asserts that the validity of a certain counterfactual statement, SR in Sec. 4 below, referring to the properties of a particular particle, depends upon the choice of which measurement is made on a different particle at a spatially distant location. He further claims that this dependence is confirmed by an approach to counterfactuals presented in Ch. 19 of the author's *Consistent Quantum Theory* [4], hereafter referred to as CQT. It will be argued that, on the contrary, the possibility of deriving the counterfactual SR depends on the point of view or perspective that is adopted—specifically on the *framework* as that term is employed in CQT—when analyzing the quantum system, and this dependence makes it impossible to construct a sound argument for nonlocality, contrary to Stapp's claim.

The study below is based upon the (“consistent” or “decoherent”) *histories* formulation of quantum mechanics. Since there is an extended treatment in CQT, a brief summary in [5], and expositions of intermediate length in [6, 7], the details need not be repeated here, though it is worth emphasizing some features of this approach. First, in contrast to standard textbook quantum mechanics the histories approach permits a discussion of *microscopic* quantum properties corresponding to subspaces of the quantum Hilbert space *without* any reference to measurements. As a result it has no measurement problem of the sort that besets standard quantum mechanics, which in its more orthodox versions is only allowed to speak about macroscopic preparations and measurement outcomes. Microscopic and macroscopic systems are addressed in the histories approach using exactly the same fundamental quantum principles, and one can explain how and why a measurement outcome (pointer position) can be related to the microscopic quantum property that precedes the measurement, the property that the measurement is intended to reveal. Because of its ability to relate measurement outcomes to prior measured properties the histories approach is sometimes thought to be a “hidden variables” theory, and then dismissed as necessarily leading to the usual paradoxes associated with such theories. But it is *classical* hidden variables which, as Stapp points out, are inconsistent with quantum principles and lead to paradoxes, whereas the histories approach employs genuine *nonclassical* microscopic (and macroscopic) quantum properties, which are treated in a consistent way that avoids paradoxes.

Counterfactuals and their use in quantum theory are discussed in Secs. 19.3 and 19.4 of CQT. A brief introduction, which should suffice for the present paper, is given in Sec. 2 below, based upon a particular (classical) example. Stapp's criticism in [1] uses a quantum state introduced by Hardy [8]. That state and some associated measurements are presented in Sec. 3 using the notation for entangled qubits (spin-half or two-state systems) common in current discussions of quantum information. Stapp's counterfactual SR is the topic of Sec. 4. Section 5 summarizes the conclusions of the paper, while Sec. 6 is an addendum with a response to comments by Stapp in the last section of [1].

2 Counterfactuals

Suppose a gun fires a bullet which comes to a stop in a block of wood separating the gun from a glass beaker. What *would have* happened *if* the wooden block had not been in the way? This is a *counterfactual* question comparing an “actual” world W_1 in which something took place, with a “counterfactual” world W_2

which resembles W_1 in certain respects, but differs from it in others. Such counterfactual reasoning is quite common in everyday experience, but trying to codify it and nail down the rules has given philosophers a lot of trouble. A fundamental difficulty is that there are often several choices for W_2 , each different from W_1 but in different respects. If counterfactual reasoning about the classical world of everyday experience involves subtleties, one should not be surprised if similar or even worse difficulties arise when trying to extend it to the quantum world.

Before discussing quantum issues let us complicate our classical example slightly by assuming that the gun can be aimed in several different directions, only one of which is towards the beaker, and the aim is determined just before the gun is fired by tossing a coin. This could be done by using the random outcome of some quantum measurement, e.g., using the number of radioactive atoms decaying during a specified time interval, though such a quantum source of randomness is not essential for the present discussion. Similarly, we might suppose that the wooden block is left in place or quickly pushed away so that it no longer protects the beaker depending on the outcome of a (suitably rapid) coin toss. Our counterfactual question as to what would have happened had the wooden block not been in the way now becomes less definite, or at least could be interpreted in more than one way. Should we be thinking that the gun actually was directed at the beaker (and thus at the wooden block) in the case of interest, or should we allow for the possibility that it might have been pointed in some other direction? The second interpretation leads to a probabilistic answer. “The beaker would have been shattered with probability $1/4$, and remained unbroken with probability $3/4$ ” is a sensible response if the gun could have pointed with equal probability in four different directions, only one of them aimed towards the beaker. Probabilistic answers to counterfactual questions can make perfectly good sense in a stochastic setting.

In CQT Ch. 19 it is suggested that quantum situations analogous to the example just discussed could be usefully analyzed in the following way. First it is necessary that all the properties, macroscopic or microscopic that one wishes to discuss, whether in W_1 or W_2 , must belong to a single quantum framework or consistent family of histories. This *single framework rule* is fundamental to quantum reasoning according to the histories approach, see Ch. 16 of CQT, so it is natural to require that it also be observed when dealing with counterfactuals. Sometimes this can be done by thinking of a closed quantum system which contains a quantum coin toss (or perhaps several tosses) with different outcomes corresponding to different worlds. Next, work backwards in time from what actually happens in W_1 to a time at which W_1 is identical to W_2 , and identify a state of affairs, called the *pivot*, which is the same in both worlds. Then apply the laws of quantum dynamics to predict, generally in a probabilistic sense, what will later take place in W_2 . It is often helpful to use a time-ordered tree diagram as an aid to analyzing the situation; several examples, both classical and quantum, will be found in Ch. 19 of CQT.

The result of this analysis will in general depend upon the framework of consistent families used to define, and differentiate, W_1 and W_2 , and on the choice of the pivot. Counterfactual questions can have a variety of answers. Another way of stating the matter is that such questions are often to a certain degree ambiguous, and thus can be interpreted in different ways. Choosing a specific framework and pivot makes the counterfactual question more precise, but then the (probabilistic) answer to the question may depend on this choice. In the previous example one might want to use a pivot that corresponds to the situation just after the gun is fired, when the direction in which it is aimed has already been decided, assuming W_1 and W_2 are at this time identical. In this case one can conclude that in the counterfactual world, with the wooden block out of the way, the bullet will certainly, with probability 1, shatter the beaker. However, if the pivot is chosen at a time before flipping the coin that determines the direction in which the gun is aimed, the answer, as noted above, is only probabilistic, and thus less definite. To be sure, one might think it more natural, and perhaps closer to everyday usage, if a “sharper” answer to a counterfactual question is preferable to a less definite one. In the situation at hand, “the beaker would have been shattered” is sharper, more definite, than the less definite probabilistic response. In any case nothing is lost by focusing attention on the precise respects in which the worlds of interest differ, and the route that leads to a particular answer to a counterfactual question.

3 Hardy’s State

In what follows it is helpful to employ an explicit wave function of the Hardy [8] type. In place of Hardy’s original notation we use one that is by now fairly familiar in discussions of quantum information. Think of two spin-half particles (qubits) a and b , where for each particle the orthonormal basis $|0\rangle, |1\rangle$ consists of

eigenkets of S_z ,

$$S_z|0\rangle = (1/2)|0\rangle, \quad S_z|1\rangle = -(1/2)|1\rangle, \quad (1)$$

in units of \hbar . The alternative orthonormal basis defined by

$$\sqrt{2}|+\rangle = |0\rangle + |1\rangle, \quad \sqrt{2}|-\rangle = |0\rangle - |1\rangle, \quad (2)$$

consists of eigenkets of S_x with eigenvalues $+1/2$ and $-1/2$, respectively. In this notation we write the Hardy state in the form

$$\sqrt{3}|\psi_0\rangle = |0\rangle_a \otimes |0\rangle_b + |0\rangle_a \otimes |1\rangle_b + |1\rangle_a \otimes |0\rangle_b \quad (3)$$

(The reader may prefer to abbreviate $|0\rangle_a \otimes |1\rangle_b$ to $|01\rangle$.) The a and b subscripts are used both to label the states and to differentiate the angular momentum operators for the two particles in an obvious way: S_{ax} , S_{bz} , etc. Once the Hardy state has been created, by whatever means, at a time t_0 it remains unchanged under unitary time development—a trivial time development operator $I_a \otimes I_b$, corresponding to zero magnetic field, so the spins do not precess—up to a time t_2 when one particle or the other begins to interact with some measuring device.

In the histories approach measurement apparatus must, at least in principle, be described in fully quantum mechanical terms. The proper way to do this in the case of idealized measuring processes is discussed extensively in CQT, see in particular Chs. 17 and 18, and more briefly in [7]. For present purposes we may assume that an apparatus designed to measure S_{bz} for particle b is initially in the state $|Z_b\rangle$. The unitary time transformation describing the result of its interacting with particle b in the time interval from t_2 to t_3 is given by

$$|0\rangle_b \otimes |Z_b\rangle \rightarrow |0\rangle_b \otimes |Z_b^+\rangle, \quad |1\rangle_b \otimes |Z_b\rangle \rightarrow |1\rangle_b \otimes |Z_b^-\rangle, \quad (4)$$

where one should think of $|Z_b^+\rangle$ and $|Z_b^-\rangle$ as macroscopically distinct, corresponding to different pointer positions in the traditional language of quantum foundations. The projectors on such states—equivalently, the corresponding properties—will be denoted by Z_b^+ and Z_b^- . One can make the model more realistic in various ways, e.g., using density operators for the apparatus, see Chs. 17 and 18 of CQT, but that is not needed for the following discussion. In a similar way an apparatus designed to measure S_{bx} for particle b starts in a state X_b , and the time transformation analogous to (4) for the time interval from t_2 to t_3 is

$$|+\rangle_b \otimes |X_b\rangle \rightarrow |+\rangle_b \otimes |X_b^+\rangle, \quad |-\rangle_b \otimes |X_b\rangle \rightarrow |-\rangle_b \otimes |X_b^-\rangle. \quad (5)$$

An apparatus designed to measure S_{bz} can be changed into one that measures S_{bx} by turning on a suitable magnetic field just ahead of the entrance of the S_{bz} device, one which causes states $S_{bx} = \pm 1/2$ to precess into states $S_{bz} = \pm 1/2$. Let us refer to these two possibilities as *measurement settings* of the apparatus, denoted by $|Z_b\rangle$ and $|X_b\rangle$ as used above. We can imagine that the presence or absence of this magnetic field is determined by a quantum coin of the sort described in CQT, at a time just before the arrival of the b particle. In the same way one can imagine that measurements of S_{az} or S_{ax} on particle a can be determined by an apparatus with settings $|Z_a\rangle$ and $|X_a\rangle$, which could be set by a different quantum coin shortly before the arrival of the a particle.

Table I relates the notation used here to that of Hardy [8] and Stapp [1]. Thus Z_a corresponds to Hardy's U_1 and Stapp's ML1, whereas the outcome Z_a^+ corresponds to $U_1 = 0$ and ML1+, and Z_a^- to $U_1 = 1$ and ML1-.

Table 1: Comparison of notation

This paper	Hardy	Stapp
$Z_a: Z_a^+, Z_a^-$	$U_1: U_1 = 0, 1$	ML1: ML1+, ML1-
$X_a: X_a^+, X_a^-$	$D_1: D_1 = 0, 1$	ML2: ML2-, ML2+
$Z_b: Z_b^+, Z_b^-$	$U_2: U_2 = 0, 1$	MR1: MR1-, MR1+
$X_b: X_b^+, X_b^-$	$D_2: D_2 = 0, 1$	MR2: MR2+, MR2-

4 Stapp's Counterfactual

Stapp's counterfactual SR [1] translated into the notation of Sec. 3 reads as follows:

SR: Suppose that S_{bz} is measured on particle b and the result is Z_b^- . Then if instead of S_{bz} , S_{bx} had been measured on particle b the result would have been X_b^+ with certainty, i.e., probability one.

One can derive SR using the approach to quantum counterfactuals in Ch. 19 of CQT *if* an appropriate choice is made for both framework and pivot. A suitable framework is the collection of histories

$$[\Psi_0] \odot \{[0]_a, [1]_a\} \odot \{X_b, Z_b\} \odot \{X_b^+, X_b^-, Z_b^+, Z_b^-\}, \quad (6)$$

with time increasing from left to right, interpreted as follows. As in CQT we use the notation $[\psi] = |\psi\rangle\langle\psi|$ for the projector onto a quantum state $|\psi\rangle$. At the initial time t_0 the quantum state is $[\Psi_0] = |\psi_0\rangle \otimes |M\rangle$, where $|\psi_0\rangle$ is the Hardy state (3) and $|M\rangle$ is the initial state of the apparatus which will later measure some component of the spin of particle b , along with the quantum coin which will determine whether the apparatus is set up to measure S_{bz} or S_{bx} . The \odot is a tensor product symbol, but for present purposes one can regard it as simply separating events at different times. At t_1 particle a is in one of the two mutually exclusive states $|0\rangle_a$ or $|1\rangle_a$, denoted by the projectors $[0]_a$ and $[1]_a$, and nothing is said about particle b or the apparatus. As usual, $[0]_a$ is equivalent to $[0]_a \otimes I_b \otimes I_M$, where I_b and I_M are the identity operators on particle b and the apparatus. At a later time t_2 the quantum coin flip results in the apparatus being in one of the two states X_b or Z_b , ready to measure S_{bz} or S_{bx} , whereas at a still later time t_3 the measurement outcomes (pointer positions) are X_b^+ , etc., in an obvious notation.

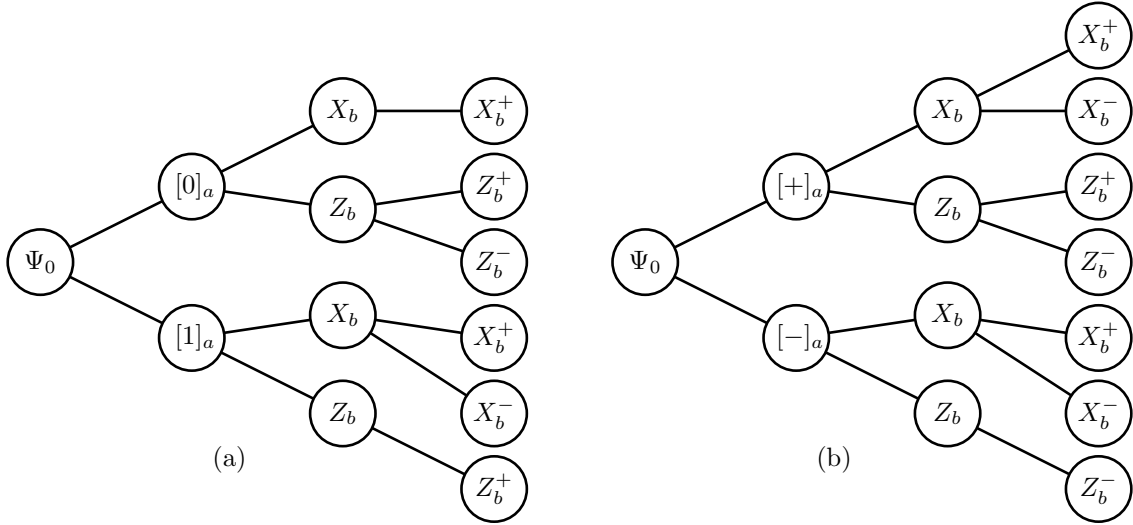


Figure 1: Diagrams for (a) the family (6); (b) the family (7).

The family of histories in (6), which is easily shown to be consistent using the methods in CQT, can also be conveniently represented in Fig. 1(a), where again time increases from left to right and the different lines correspond to the different histories which occur with finite probability. Thus the line from Ψ_0 that terminates in the second node from the top, labeled Z_b^+ , in the right column indicates a history in which, starting from the initial state, the a particle was at time t_1 in $|0\rangle_a$, $S_{az} = +1/2$, the quantum coin flip resulted in Z_b , thus S_{bz} and not S_{bx} being measured, with an eventual measurement outcome of Z_b^+ . The other lines have analogous interpretations. Two of the nodes one might have expected in the right hand column are absent: following $[0]_a$ and X_b there is no X_b^- , and following $[1]_a$ and Z_b there is no Z_b^- . This is because the probabilities of these histories are zero: they never occur.

Using Fig. 1(a) based on (6) it is possible to derive the counterfactual statement SR in the following way. Suppose S_{bz} is measured and the outcome is Z_b^- . The Z_b^- node only occurs in the upper half of the diagram, and tracing this history backwards in time one concludes that at an earlier time particle a was in

the state $[0]_a$. Using this node as the pivot, and assuming that in the counterfactual world the quantum coin toss resulted in X_b rather than Z_b , follow the line from $[0]_a$ to X_b and then on to X_b^+ . The conclusion is that had S_{bx} been measured the result would have been X_b^+ with certainty, probability one.

However, (6) is not the only framework or family of histories one might use to analyze the situation. An alternative family

$$[\Psi_0] \odot \{[+]_a, [-]_a\} \odot \{X_b, Z_b\} \odot \{X_b^+, X_b^-, Z_b^+, Z_b^-\}, \quad (7)$$

differs from (6) only in that the possible properties of particle a at time t_1 are now the eigenstates of S_{ax} instead of S_{az} . As the projectors associated with S_{ax} do not commute with those associated with S_{az} the two families in (6) and (7) are incompatible: the results of reasoning using one cannot be combined with results using the other; this is the single framework rule discussed at length in CQT. The family (7) corresponds to the diagram in Fig. 1(b), which resembles (a), but differs from it in two respects, in addition to the fact that the $[0]_a$ and $[1]_a$ nodes have been replaced with $[+]_a$ and $[-]_a$. First, the node Z_b^- , the starting point of the counterfactual SR, occurs *twice* at the final time t_3 ; it follows both $[+]_a$ and $[-]_a$. Therefore one cannot conclude from Z_b^- that S_{ax} had a particular value at t_1 : it could have been either positive or negative. Second, both of the X_b nodes at time t_2 are followed by both possible outcomes, X_b^+ and X_b^- , with finite probabilities. Either of these changes is enough to prevent the derivation of SR in its precise form, given above, if one uses the family (7). One would, instead, have to be content with a weaker form in which SR would end with: "...the result would have been X_b^+ with a probability p ." Here p is some probability less than 1.

Thus the strict counterfactual SR (conclusion with probability 1) can be derived using a certain consistent family, but only a weaker version can be obtained using a different family. Which is correct? In the quantum world, no less than in the classical world, there is in general no "right" way to discuss counterfactuals. Would the beaker have been shattered if the board had not been in place? The answer depends, as discussed in Sec. 2, on how one goes about addressing the question, which is to say how one makes it more precise by specifying the ways in which world W_2 coincides with and how it differs from W_1 . That there is a particular framework in which SR (in its original strict form) can be derived is a nontrivial results that depends, among other things, on the form of the Hardy state (3). One could adopt the convention that SR is correct provided one can find *at least one* framework and pivot which justifies it, and in that case it follows from the argument based on (6) and Fig. 1(a); the existence of other frameworks or pivots that lead to less definite results is irrelevant. The classical example analyzed in Sec. 2 would suggest that such a convention is not implausible, but it would in any case be a convention; there are no strict and universally accepted rules for how to handle counterfactual arguments. Stapp, in particular, does not accept this convention [9].

The preceding discussion employs *properties* of particle a and makes no reference to *measurements* on particle a . In contrast to textbook quantum mechanics, the histories approach allows statements to be made about microscopic properties without reference to measurements. However, the arguments we have just presented, and the diagrams in Fig. 1, remain perfectly valid if one allows particle a to interact at some time later than t_1 with an apparatus (which must, of course, be included in the analysis as part of the total quantum system) whose setting of $|Z_a\rangle$ or $|X_a\rangle$, to measure S_{ax} or S_{az} , may be chosen by a quantum coin near this apparatus just before the arrival of particle a . As neither of the families in (6) or (7) makes any reference to the later measurement on particle a or its outcome, the probabilities employed in constructing them, and therefore the diagrams in Fig. 1(a) and (b) remain unchanged. So again there is at least one framework in which SR can be derived, and another (in fact many others) in which only a weakened form, with probability $p < 1$, can be obtained. If one adopts the convention (which, as noted above, Stapp rejects) that the sharpest answer to a counterfactual question, the most precise one that can be found considering different frameworks and pivots, is the correct one, SR is always correct, independent of the outcome of the quantum coin flip that results in $|X_a\rangle$ or $|Z_a\rangle$. In particular the families in (6) and (7) remain consistent if the set of events at time t_2 is augmented so that $\{X_b, Z_b\}$ is replaced with the four possibilities $\{X_a X_b, X_a Z_b, Z_a X_b, Z_a Z_b\}$. (We remind the reader that the product PQ of two commuting projectors P and Q is to be interpreted as the conjunction of the properties: P AND Q .)

But what can one say about measurement *outcomes* on the a side? Here care is needed: it is not possible to add the outcomes X_a^-, X_a^+ for particle a to the family (6), nor is it possible to add the outcomes Z_a^-, Z_a^+ to the family in (7), without violating consistency conditions and thus rendering the family meaningless. One can, on the other hand, achieve consistency in both cases either by saying nothing (use the quantum identity operator) or by using appropriately chosen macroscopic quantum superpositions—MQS or Schrödinger cat state—in place of the pointer basis. The reader is referred to the discussion in Sec. 19.4 of CQT, e.g., that

associated with Eq. (19.12), and we leave it as an exercise to work out which MQS and which “ordinary” or “pointer” states are permitted by the consistency conditions in the situation under consideration here. It should be emphasized that the histories approach does *not* have an automatic commitment to using the pointer basis: while in many situations it is the most useful description to employ in terms of what one is interested in discussing, this is a matter of utility, not necessity.

Thus whether or not one can derive SR (in the precise, not the weakened, form) is very much a matter of the choice of framework and pivot. There is always at least one framework and pivot for which the such a derivation is possible, and this is true for either outcome of the quantum coin flip that determines the measurement settings $|Z_a\rangle$ or $|X_a\rangle$ for the apparatus that will interact with particle a . Stapp has made a particular choice of framework, one might call it a “hybrid,” in which the derivation of SR is possible when the coin results in $|Z_a\rangle$ but not when it results in $|X_a\rangle$. However, there is an alternative choice of framework, in which the pointer basis is replaced by suitable MQS states, for which in the $|Z_a\rangle$ case the derivation of SR is impossible, but is possible in the case $|X_a\rangle$! From the perspective of fundamental quantum theory there is no reason to prefer one of these frameworks to the other.

Some additional points. First, the dependence of counterfactual conclusions on the framework and pivot was pointed out explicitly in CQT, both in Ch. 19 where counterfactuals are first discussed, and in Ch. 25 where they are applied to the paradox presented in an earlier paper by Hardy [10]. It is not an idea developed more recently in order to respond to [1]. Second, the choice of framework (and pivot) is one made by the physicist in constructing a description of the quantum world, and is not some sort of “physical influence” upon that world. See the discussion in Sec. 27.3 of CQT. A quantum framework is something like a point of view. A coffee cup looks different when viewed from below than when viewed from above. Changing the viewpoint does not change the cup, though it changes what one knows or can say about the cup. Third, as long as there is no interaction between particles a and b following their preparation, the temporal ordering of events on the a (left) side relative to those on the b (right) side—e.g., whether measurements are carried out first on particle a or first on particle b —makes no difference whatsoever for the consistency of the different families or the probabilities of events within one family. One can even assume that the measurements on b occur inside the backward light cone of the measurements on a , or vice versa; see the discussion of such situations in [7]. This is precisely what one would expect to be the case in the *absence* of any nonlocal influences of the sort that Stapp claims exist, so it is an additional confirmation of their nonexistence.

5 Conclusion

What we have shown is that, given the Hardy state and appropriate settings for measurements on particle b , there are frameworks, with (6) an example, in which it is possible to use the method of counterfactual reasoning presented in Ch. 19 of CQT in order to derive Stapp’s SR in its strict form (probability 1), while there are other frameworks, for example (7), in which such a derivation is not possible, and one can only obtain a weaker, probabilistic form of SR. The example given by Stapp in [1] is a combination of the two, a framework in which SR can be derived provided a quantum coin results in a measurement setting $|Z_a\rangle$ for the distant particle a and one uses a pointer basis for the measurement outcomes, whereas the derivation is not possible if the coin leads to the setting $|X_a\rangle$ and one again employs the pointer basis. However, this fails to prove the existence of nonlocal influences in quantum mechanics because, as discussed in Sec. 4, there are alternative frameworks in which one can arrive at different results. In particular, there is a framework in which the case $|Z_a\rangle$ followed by an MQS basis makes the derivation of SR impossible, whereas in the case $|X_a\rangle$ one can derive SR. The existence of these different frameworks undermines any argument for nonlocality which depends upon a particular choice among them.

Thus what Stapp has shown is not the existence of quantum nonlocality, but instead the inadequacy of counterfactual reasoning of the sort he is advocating for analyzing situations of this kind. Fortunately, there are other approaches to answering the question of nonlocal influences. Neither Stapp nor anyone else has yet found a defect in the relatively straightforward (no counterfactuals) demonstration of the principle of Einstein locality given in [2], a principle which directly contradicts Stapp’s claims of nonlocality.

None of this should be taken to imply that the study of counterfactual reasoning in the quantum domain is impossible or uninteresting or must always lead to ambiguous results. Instead, it is a tool that needs to be used carefully, with full recognition of its ambiguities and the possibility that it can mislead, especially if one employs inconsistent ideas, such as the treatment of measurement using wave function collapse found in current textbooks, rather than starting off with a sound formulation of quantum mechanics that is consistent with the mathematical structure of Hilbert space.

6 Final Note

The preceding sections were written before seeing the final section, “Response to Griffiths’ Reply”, in [1]. Hopefully the following remarks will enable the reader to better understand the points at which Stapp and I differ, and assess the merits of each position. Before mentioning the differences it is worth emphasizing that there are significant points on which we agree. Stapp prefers to use a framework which only includes macroscopic outcomes of measurements, and he is free to do so. His conclusions drawn from this frameworks about the correctness, or let us say the derivability, of the counterfactual SR, are in accord with the inference scheme given in Ch. 19 of CQT. The same is true of the frameworks I prefer (and am free) to use, those shown in Fig. 1, which include microscopic properties of particle a but make no reference to measurements on this particle or their outcomes. (It is typical of the histories approach that different frameworks can be employed, and there is no law of nature which specifies the “correct” framework. Frameworks are chosen on the basis of what issues one wants to discuss, and there is a very general argument, Ch. 16 of CQT, for the overall consistency of the histories approach provided one pays strict attention to its single framework rule, which forbids combining incompatible frameworks.)

Our major disagreement is over the conclusions which can be drawn from these analyses. Stapp believes that because he has identified a framework which properly corresponds to his earlier argument for nonlocal influences, and in this framework the ability to deduce SR is linked to which measurement is carried out on particle a , this demonstrates a nonlocal influence on particle b . I disagree, because there exist alternative frameworks in which there is no such link between measurement choices on a and the derivation of SR for b . The existence of alternative frameworks in which one can draw different conclusions is already present in the case of classical counterfactuals, as discussed in Sec. 2, and one cannot expect the quantum situation to be any simpler. So why believe a conclusion found in one framework but not supported by a similar analysis in another? The reader will have to judge whether Stapp makes a convincing case for nonlocality or whether, as is my opinion, he has only demonstrated the hazards involved in trying to use this mode of counterfactual reasoning to reach sound conclusions about the quantum world.

Another point of agreement is that my proof of Einstein locality in [2] is correct about what it asserts when it is applied to the present situation in the following way: Let there be a third particle c which is initially in one of two states $|c\rangle = |0\rangle$ or $|1\rangle$. Let it interact with the measuring apparatus associated with particle a *after* that particle has been separated from particle b , in particular after the preparation of both particles in the entangled Hardy state (3), in such a way that if $|c\rangle = |0\rangle$ the apparatus will measure S_{az} , and if $|c\rangle = |1\rangle$ the apparatus will measure S_{ax} . Then the probabilities of any sequence of events involving the distant particle b or its measurement apparatus will be *exactly the same* whatever the initial state, $|0\rangle$ or $|1\rangle$, of c .

Our disagreement is about whether Einstein locality in this form rules out any nonlocal influence by the choice of measurement (as determined by c) on particle a , on the distant particle b . My position is that since this measurement choice has no effect upon the probabilities which describe b or its associated measurement apparatus, it has no “influence” in any sense akin to the usual notion of physical influence. Stapp asserts that the influence is not one that is revealed by probabilities, but by something else. I confess I do not understand his reasoning at this point, so must leave it to the reader to assess its validity. He also asserts that the omission of a counterfactual discussion from my derivation of Einstein locality represents a severe deficiency, a fatal flaw. Here again we disagree; Stapp has much more confidence in the soundness of his counterfactual approach than do I. So again the reader must judge. Let me add that while the basics of the histories approach as presented in CQT seem fundamentally sound—or at least no significant flaws have thus far been pointed out by critics [11]—the part in Ch. 19 having to do with counterfactual reasoning is more tentative than the rest. In particular, it involves the direction (past versus future) of time in a way not present in the main formalism, which is time symmetric. Revisions of this aspect of the histories approach to quantum counterfactuals, which has a very definite time asymmetry, may be needed when the problem of thermodynamic irreversibility has been better understood in quantum terms.

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